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THE DETERMINATION OF OPTIMUM PARAMETERS FOR MULTI-PERFORMANCE CHARACTERISTICS IN PULSED GAS METAL ARC WELDING OF AISI 904 L SUPER AUSTENITIC STAINLESS STEEL USING GREY RELATIONAL ANALYSIS

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ABSTRACT

Welding input parameters play a vital role in determining the quality of a weld joint. The quality of the joint can be defined in terms of mechanical properties and weld-bead geometry. Generally, all welding processes are employed with the aim of obtaining a welded joint with the desired characteristics. The purpose of this study is to propose a method to decide near optimal settings for the welding process parameters in pulsed gas metal arc welding (P-GMAW) of AISI 904L super austenitic stainless steel by using grey relational analysis. Grey relational analysis was applied to optimize the input parameters by considering multiple output variables simultaneously. The welds were performed on a sheet with a thickness of 5 mm and a filler wire of diameter of 1.2 mm and their levels of different process parameters were Peak Current (Ip), Pulse Time (tp), Pulse Frequency (f), back ground current (Ib) and welding speed (S) which were considered as input responses. The central composite rotatable design was used to carry out the experimental design and predict the effects of input and output responses. In this study, the output responses considered were bead width, tensile strength, % of elongation, impact strength and microhardness of the welds. The main objective of this work is to determine the P-GMAW process parameters to maximize the tensile strength, % of elongation, impact strength and microhardness and minimize the bead width of the processed joints. This study describes how to obtain near optimal welding conditions over a wide search space by conducting relatively a smaller number of experiments. ANOVA analysis was carried out to identify the significant factors affecting tensile strength, % of elongation, impact strength, microhardness and bead width and further to experimentally validate the optimized parameters. Further investigation was carried out to study the mechanical and metallurgical properties of the optimized parameter weld joints.

KEYWORDS: ***P-GMAW, Tensile Strength, Impact Strength, Microhardness, Weld Bead Width & Grey Relational Analysis***

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Original Article

1 INTRODUCTION

The quality of the weld joint is largely determined by the optimal selection of arc voltage and welding current. It is reported that variation of the rated values of arc voltage and welding current leads to defects like spatter, lack of fusion and melt through etc. These variations mainly depend on the power source construction and it is difficult to generalize in terms of analytical or empirical models. This is primarily due to lack of understanding of characteristic response to current and voltage relationship under static and dynamic conditions of welding resulting in more complication to operate the welding process in critical applications. Therefore, metal transfer in conventional GMAW cannot be regulated as independent of heat input, but, in pulsed gas metal arc welding

(P-GMAW) process, due to intermittent pulses of high current, spray transfer may be obtained at a comparatively lower level of heat input. In this process, current is periodically modulated between a lower level of base current and higher level of peak current. AISI 904 super austenitic stainless steel normally contains high amount of Mo, Cr, Ni, N and Mn. Since the steel retains its corrosion resistance at moderate and high temperature, it is utilized extensively in the chemical, pulp paper and pollution control industries.

Nowadays, application of the new design of experiment (DoE), evolutionary algorithms and computational network is mostly used to develop mathematical relationships between the welding process input parameters and the output variables of the weld joint in order to find out the welding input parameters that lead to the desired weld quality. Taguchi method was applied to optimize the process parameters, namely current, voltage and welding speed to obtain maximum depth of penetration on mild steel [1]. The effect of process parameter on the weld bead hardness of AISI 1020 material for TIG and MIG welding processes using grey relational analysis (GRA) was investigated [2]. Mathematical model equations were obtained for pulsed TIG welding of titanium sheets and it was concluded that the mathematical relationships developed can be employed easily in automated welding in the form of a program, for obtaining the desired weld bead dimensions [3]. The process parameters were optimized for enhancing the mechanical properties of MIG welded aluminium alloy joints (Al-65032) [4].

The factorial design approach was adopted to examine the Metal Inert Gas welding variables (viz. Current of welding, welding speed, and welding arc voltage and stick-out distance of electrode) on aluminium by measuring the geometry of weld bead and penetration of the weld. For sound quality bead width, bead penetration and weld reinforcement on butt joint were investigated by the development of a mathematical model. The welding current was found to be the most influencing parameter on the weld geometry [5]. The output response, namely tensile strength was recorded for its corresponding parameters of MIG welding, such as current, arc voltage, welding speed and shielding gas flow. It was noted that the tensile strength increased with increasing the welding current [6]. TIG welding process parameters (viz. travel speed of welding, current and flow rate of gas) on welding of aluminium were examined and also the methodology of response surface to perform the experiments for measuring the strength of weld joints was used. It was noted that welding current was a highly influencing parameter on the tensile strength and percent elongation [7]. A study was focused on the effect of gas pressure, current, angle of groove and preheat on MIG welding of Al- 65032 by Taguchi method. The current of welding was found to influence the ultimate tensile strength. The significant variables for proof stress, elongation and impact energy are found to be the pressure of gas [8]. The author investigated tensile strength in AZ31B magnesium alloy by the effect of pulsed current gas tungsten arc welding. The tensile strength was greatly influenced by pulse frequency followed by peak current, pulse on-time and base current [9]. A mathematical model was developed with respect to the current and voltage in TIG welding as quadratic polynomials based on the sheet thickness. Theresults were presented for algorithmic optimization in the case of T-joint with fillet weld [10]. A sensitivity analysis of a robotic GMAW (gas metal arc welding) process was conducted to determine the effect of measurement errors on the uncertainty in estimated parameters. They employed non-linear multiple regression analysis for modelling the process and quantified the respective effects of process parameters on the weld bead geometric parameters [11]. The author compared the experimental data obtained for weld bead geometry with those obtained from empirical formulae in gas metal arc welding (GMAW) [12].

The weld bead geometry of the super austenitic stainless steel sheets using laser welding was studied. Taguchi technique was applied to conduct the experiments. The output variables were bead width, depth of penetration and aspect ratio. The input parameters were beam power, travel speed and focal position [13]. The effects of different parameters such as arc voltage, welding current and welding speed on welding penetration, microstructure and hardness measurement in mild steel having 6mm thickness of base metal was studied by using the robotic GMAW. As a result, it was noted that increasing the parameter value of welding current increased the value of depth of penetration. Other than that, arc voltage and welding speed were the other factors that influenced the value of depth of penetration [14]. Parametric optimization in GMAW and GTAW on AISI 1020 steel by using ANOVA and GRAwas done. Welding current, wire diameter and wire feed rate were taken as input parameters for GMAW and the output parameter was hard. For GTAW, the input parameters were welding current, wire diameter and the output parameter was hard. In both cases, welding current predominantly influenced the hardness [15]. Taguchi approach with ANOVA was used to arrive at the optimum set of laser welding parameters for achieving good mechanical properties tested by notched tensile specimen for a dissimilar combination of AISI 316 austenitic stainless steel to AISI 1008 low carbon steel. The mechanical properties of welded joints with optimum parameters were found to be better than the base material. It was found that laser power was to be the most influencing factor in determining the strength of such dissimilar joints. The authors also optimised the parameters for obtaining good fusion zone properties for the same combination of materials and they found that with respect to the fusion zone properties, welding speed had the greatest influence [16 &17]. The optimisation technique was found to be a very useful tool even for welding of non-metals like plastics.

A method was proposed to decide near the optimal settings of a GMAW welding process. Near-best values of three control variables (welding voltage, wire feed rate and welding speed) based on four quality responses (deposition efficiency, bead width, depth of penetration and reinforcement), inside a previous delimited experimental region were chosen. The search for the near-optimal setting was carried out step by step, using genetic algorithm. The proposed GA manages to locate near optimum conditions, with a relatively small number of experiments [18]. Some of these studies [19-21] considered only a single output as the response, and a mathematical model was developed which can accurately predict the output for a particular combination of input parameters. This modelling was done based either on response surface methodology or intelligent methods like artificial neural network. The Taguchi method is very popular for solving optimization problems in the field of production engineering [22]. The method utilizes a well balanced experimental design (allows a limited number of experimental runs) called orthogonal array design, and signal-to-noise ratio (S/N ratio), which serve the objective function to be optimized (maximized) within the experimental domain. However, the traditional Taguchi method cannot solve multi-objective optimization problem. To overcome this, the Taguchi method coupled with Grey relational analysis is employed [23–25]. This approach can solve multi response optimization problem simultaneously. It is appropriate to apply this technique to a complex system like welding process. Apart from process optimization, it is necessary to determine the degree of significance of the factors on the output features of the final product. This statistical significance of the factors can be evaluated through analysis of variance (ANOVA).

From the above literatures, it is clear only a few works have been carried out in optimization and characterization of AISI super austenitic stainless steel. It was also clear that GRA can be used to optimize the P-GMAW welding process parameter to obtain the desired quality weldments. In this work, multi-objective optimization using GRA was carried out to optimize the P GMAW welding process parameters (Peak Current (I_p), Pulse Time (t_p), Pulse Frequency (f), back ground current (I_b) and welding speed (S)). The output responses were bead width, tensile strength, % of elongation, impact

strength and microhardness of the weld. By analysing the grey relational grade, the most influential factor was determined. ANOVA method was applied to find the percentage effect of individual parameters. Further, the confirmation test was carried out to validate the optimized set of parameters through mechanical and metallurgical characterization of the weld.

2. EXPERIMENTAL PROCEDURE

The welding trials were carried out on 5 mm thick sheet of AISI 904 L super austenitic stainless steel using P-GMAW process with argon as shielding media. The chemical composition of the base material is presented in Table 1. Super austenitic stainless steel filler wire of diameter of 1.2 mm was used. Butt weld experiments were conducted on 150mmx75mmX5 mm thick sheets. Joints prior to welding contact surfaces were cleaned with fresh stainless steel wire brush, followed by acetone swabbing.

Table 1: Base Material Chemical Composition (Weight in %)

Material	Si	Mn	P	S	Cr	Ni	Mo	C	Cu	Nb	V	Co	Fe
904L	0.409	1.402	0.035	0.021	20.850	23.125	4.102	0.020	1.327	0.023	0.066	0.017	47.886

Before welding the plates were cleaned with acetone and the plates were rigidly fixed to avoid distortion during welding. Single V groove joint design was used. The welding parameters used for present investigations are given in Table 2. The other parameters kept as constant were: wire feed rate-6.5 m/min, shielding gas flow rate-15 lpm, stand of distance-1.5 mm and 'V' groove angle-60^0.

Table 2: Welding Process Parameters and Their Levels

Parameters	Symbol	-2	-1	0	1	2
Peak Current	I_p	340	350	360	370	380
Pulse Time	t_p	2.1	2.4	2.7	3	3.3
Pulse Frequency	f	120	125	130	135	140
Background Current	I_b	70	75	80	85	90
Welding Speed	S	30	35	40	45	50

The actual levels of the variables for each of the 32 experiments in the Central composite rotatable design matrix are given in Table 3.

Table 3: Coded and Actual Levels of the Five Variables

Exp. No.	I_p	t_p	f	I_b	S	I_p (Amps)	t_p (Sec)	f (Hz)	I_b (Amps)	S (mm/sec)
Factorial Point										
01	-1	-1	-1	-1	1	350	2.4	125	75	45
02	1	-1	-1	-1	-1	370	2.4	125	75	35
03	-1	1	-1	-1	-1	350	3	125	75	35
04	1	1	-1	-1	1	370	3	125	75	45
05	-1	-1	1	-1	-1	350	2.4	135	75	35
06	1	-1	1	-1	1	370	2.4	135	75	45
07	-1	1	1	-1	1	350	3	135	75	45
08	1	1	1	-1	-1	370	3	135	75	35
09	-1	-1	-1	1	-1	350	2.4	125	85	35
10	1	-1	- 1	1	1	370	2.4	125	85	45
11	-1	1	-1	1	1	350	3	125	85	45
12	1	1	- 1	1	-1	370	3	125	85	35
13	-1	-1	1	1	1	350	2.4	135	85	45
14	1	-1	1	1	-1	370	2.4	135	85	35

Table 3: Contd.,

15	-1	1	1	1	-1	350	3	135	85	35
16	1	1	1	1	1	370	3	135	85	45
Axial Point										
17	-2	0	0	0	0	340	2.7	130	80	40
18	2	0	0	0	0	380	2.7	130	80	40
19	0	-2	0	0	0	360	2.1	130	80	40
20	0	2	0	0	0	360	3.3	130	80	40
21	0	0	-2	0	0	360	2.7	120	80	40
22	0	0	2	0	0	360	2.7	140	80	40
23	0	0	0	-2	0	360	2.7	130	70	40
24	0	0	0	2	0	360	2.7	130	90	40
Centre Point										
25	0	0	0	0	-2	360	2.7	130	80	30
26	0	0	0	0	2	360	2.7	130	80	50
27	0	0	0	0	0	360	2.7	130	80	40
28	0	0	0	0	0	360	2.7	130	80	40
29	0	0	0	0	0	360	2.7	130	80	40
30	0	0	0	0	0	360	2.7	130	80	40
31	0	0	0	0	0	360	2.7	130	80	40
32	0	0	0	0	0	360	2.7	130	80	40

The P-GMAW welds are shown in Figure 1.

Figure 1: Photograph Views of P-GMAW Joints

Weld profiles were obtained by sectioning and polishing with suitable abrasive and diamond paste. Weld samples were etched with 10% oxalic acid, an electrolyte, to state and increase the contrast of the fusion zone with the base metal. The bead width and depth of the penetrations were measured by optical microscopy and some of the bead profiles are shown in Figure 2. From Figure 2, it is perceived that in most of the bead profiles, the depth of penetration is obtained in full thickness of the sheet. Hence, from bead morphology i.e., bead width was alone taken to account for optimization. When we consider the tensile strength, it becomes essential for the full penetration of the joints.

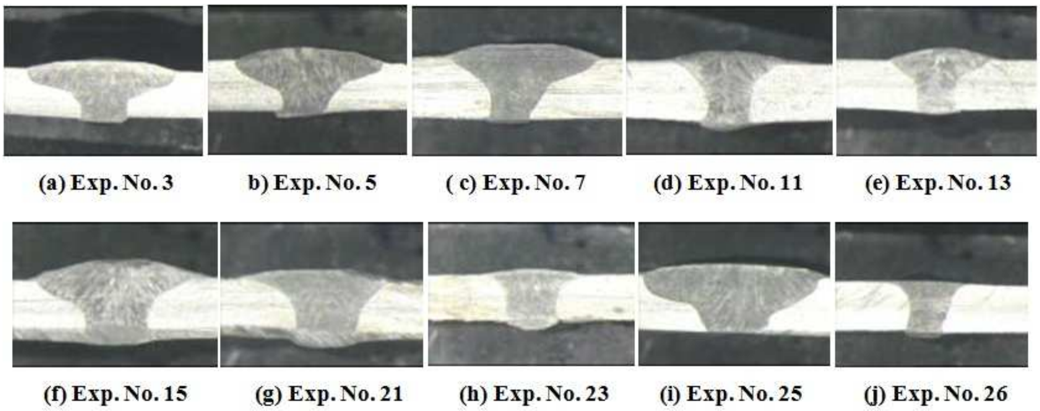


Figure 2 (a-j): Typical Weld Bead Profiles of the Joints

The tensile samples were prepared according to the AWS B 4.0 sub standards and tests were carried out at room temperature using Hounsfield Tensometer. In order to evaluate the Charpy impact toughness values of welded joints, a series of Charpy V-notch test were carried out on P-GMAW joints at room temperature. The specimens for Charpy test were taken as perpendicular to weld direction according to the ASTM: E23. Notches were prepared exactly at the midpoint of the weld. Impact test was conducted for all welded samples and the value of the impact strength was recorded. The microhardness of weldment was measured in transverse direction using a Metco SMV 1000 micro Vickers hardness machine under 1-kg load, maintained for dual time 15 seconds. The measured experimental results i.e. tensile strength, % of elongation, hardness, impact strength and bead width of the welds are shown in Table 4.

Table 4: Experimental Results

Exp. No.	I_p (Amps)	t_p (Sec)	f (Hz)	I_b (Amps)	S (mm/sec)	TS (MPa)	IS (J)	Hardness (Hv)	% Elongation	Bead Width (mm)
01	350	2.4	125	75	45	497	64	391	37	10.22
02	370	2.4	125	75	35	444	55	368	31	11.13
03	350	3	125	75	35	441	51	373	30	15.52
04	370	3	125	75	45	507	45	394	37	13.27
05	350	2.4	135	75	35	501	46	391	37	16.18
06	370	2.4	135	75	45	460	52	375	32	11.22
07	350	3	135	75	45	482	72	369	35	16.04
08	370	3	135	75	35	478	50	360	34	12.28
09	350	2.4	125	85	35	462	35	377	32	14.67
10	370	2.4	125	85	45	480	61	338	34	16.39
11	350	3	125	85	45	618	48	443	40	10.12
12	370	3	125	85	35	645	51	376	45	16.64
13	350	2.4	135	85	45	626	61	380	42	10.92
14	370	2.4	135	85	35	546	56	382	38	16.91
15	350	3	135	85	35	660	55	366	47	18.28
16	370	3	135	85	45	640	45	392	44	11.41
17	340	2.7	130	80	40	614	55	420	39	14.54
18	380	2.7	130	80	40	591	52	358	38	10.73
19	360	2.1	130	80	40	615	65	351	40	12.32
20	360	3.3	130	80	40	613	56	332	39	15.13
21	360	2.7	120	80	40	634	52	303	43	10.84
22	360	2.7	140	80	40	613	50	454	40	17.36
23	360	2.7	130	70	40	637	52	373	43	10.95
24	360	2.7	130	90	40	639	56	481	44	10.83
25	360	2.7	130	80	30	642	50	392	45	19.12

Table 4: Contd.,

26	360	2.7	130	80	50	635	62	368	43	11.42
27	360	2.7	130	80	40	619	48	221	40	10.53
28	360	2.7	130	80	40	619	48	221	40	10.53
29	360	2.7	130	80	40	620	48	221	41	11.53
30	360	2.7	130	80	40	619	48	221	40	10.53
31	360	2.7	130	80	40	621	48	221	40	10.53
32	360	2.7	130	80	40	622	49	221	41	11.53

3 RESULTS AND DISCUSSIONS

3.1 Implementations of Solution Methodology

3.1.1 Grey Relational Analysis

Grey relational analysis is a Multi criterion decision making technique which is widely used in welding related processes for selecting the optimized parameter combination. GRA is simple, easy to implement technique and even with less number of data, it has the ability to examine the correlation among the sequences and various aspects.

GRA involves the following five steps namely,

- Normalization of the performance characteristics
- Finding sequential Normalized values
- Calculating the Grey relational coefficient
- Calculation of Grey relational Grade
- Ranking the Grey relational grade with maximum value as no 1 rank.

Generally GRA involves three types of Performance characteristic analysis, namely higher the better; lower the better and nominal the better. In this work tensile strength, impact strength, percentage elongation, microhardness comes under the higher the better criteria whereas the bead width falls under the lower the better criteria. S/N ratios for all the performance characteristics were calculated by using the Equations (1) and (2).

For higher the better case, normalization was done using Equation (1)

$$Y_i^*(A) = \frac{y_i(A) - \min y_i(A)}{\max y_i(A) - \min y_i(A)} \tag{1}$$

Where i = 1…u

A =1, 2, 3…v.

u= no. of trial data

v= no. of factors

$y_i(A)$ = original sequence,

$y_i^*(A)$ value after GRG,

Min $y_i(A)$ and max $y_i(A)$ are the minimum and maximum value of $y_i(A)$ respectively. For smaller the better criterion, Normalization was done using Equation (2)

$$Y_i^*(A) = \frac{\max y_i(A) - y_i(A)}{\max y_i(A) - \min y_i(A)} \tag{2}$$

The normalized values are summarized in Table 5.

Table 5: Normalised Values of the Output Parameters

Exp no	TS (Mpa)	IS (J)	Hardness (HV)	% Elongation	Bead Width (mm)
1	0.255707763	0.783783784	0.653846154	0.411764706	0.988888889
2	0.01369863	0.540540541	0.565384615	0.058823529	0.887777778
3	0	0.432432432	0.584615385	0	0.4
4	0.301369863	0.27027027	0.665384615	0.411764706	0.65
5	0.273972603	0.297297297	0.653846154	0.411764706	0.326666667
6	0.086757991	0.459459459	0.592307692	0.117647059	0.877777778
7	0.187214612	1	0.569230769	0.294117647	0.342222222
8	0.168949772	0.405405405	0.534615385	0.235294118	0.76
9	0.095890411	0	0.6	0.117647059	0.494444444
10	0.178082192	0.702702703	0.45	0.235294118	0.303333333
11	0.808219178	0.351351351	0.853846154	0.588235294	1
12	0.931506849	0.432432432	0.596153846	0.882352941	0.275555556
13	0.844748858	0.702702703	0.611538462	0.705882353	0.911111111
14	0.479452055	0.567567568	0.619230769	0.470588235	0.245555556
15	1	0.540540541	0.557692308	1	0.093333333
16	0.908675799	0.27027027	0.657692308	0.823529412	0.856666667
17	0.789954338	0.540540541	0.765384615	0.529411765	0.508888889
18	0.684931507	0.459459459	0.526923077	0.470588235	0.932222222
19	0.794520548	0.810810811	0.5	0.588235294	0.755555556
20	0.785388128	0.567567568	0.426923077	0.529411765	0.443333333
21	0.881278539	0.459459459	0.315384615	0.764705882	0.92
22	0.785388128	0.405405405	0.896153846	0.588235294	0.195555556
23	0.894977169	0.459459459	0.584615385	0.764705882	0.907777778
24	0.904109589	0.567567568	1	0.823529412	0.921111111
25	0.917808219	0.405405405	0.657692308	0.882352941	0
26	0.885844749	0.72972973	0.565384615	0.764705882	0.855555556
27	0.812785388	0.351351351	0	0.588235294	0.954444444
28	0.812785388	0.351351351	0	0.588235294	0.954444444
29	0.817351598	0.351351351	0	0.647058824	0.843333333
30	0.812785388	0.351351351	0	0.588235294	0.954444444
31	0.821917808	0.351351351	0	0.588235294	0.954444444
32	0.826484018	0.378378378	0	0.647058824	0.843333333

The calculated sequential normalised values of the output parameters are presented in Table 6.

Table 6: Sequential Normalised Values of the Output Values

TS (Mpa)	IS(J)	Hardness (HV)	% Elongation	Bead width (mm)
0.744292	0.216216	0.346154	0.588235	0.011111
0.986301	0.459459	0.434615	0.941176	0.112222
1	0.567568	0.415385	1	0.6
0.69863	0.72973	0.334615	0.588235	0.35
0.726027	0.702703	0.346154	0.588235	0.673333
0.913242	0.540541	0.407692	0.882353	0.122222
0.812785	0	0.430769	0.705882	0.657778
0.83105	0.594595	0.465385	0.764706	0.24
0.90411	1	0.4	0.882353	0.505556
0.821918	0.297297	0.55	0.764706	0.696667

0.191781	0.648649	0.146154	0.411765	0
0.068493	0.567568	0.403846	0.117647	0.724444
0.155251	0.297297	0.388462	0.294118	0.088889
0.520548	0.432432	0.380769	0.529412	0.754444
0	0.459459	0.442308	0	0.906667
0.091324	0.72973	0.342308	0.176471	0.143333
0.210046	0.459459	0.234615	0.470588	0.491111
0.315068	0.540541	0.473077	0.529412	0.067778
0.205479	0.189189	0.5	0.411765	0.244444
0.214612	0.432432	0.573077	0.470588	0.556667
0.118721	0.540541	0.684615	0.235294	0.08
0.214612	0.594595	0.103846	0.411765	0.804444
0.105023	0.540541	0.415385	0.235294	0.092222
0.09589	0.432432	0	0.176471	0.078889
0.082192	0.594595	0.342308	0.117647	1
0.114155	0.27027	0.434615	0.235294	0.144444
0.187215	0.648649	1	0.411765	0.045556
0.187215	0.648649	1	0.411765	0.045556
0.182648	0.648649	1	0.352941	0.156667
0.187215	0.648649	1	0.411765	0.045556
0.178082	0.648649	1	0.411765	0.045556
0.173516	0.621622	1	0.352941	0.156667

Grey Relational Coefficient (GRC): GRA is employed to evaluate the relationship among two systems. The sequences applied in GRA are known as GRC. The computation of GRC was done with the help of Equation (3)

$$\lambda_i(A) = \frac{\Delta m + \tau \Delta max}{\Delta_{oi}\,(K) + \tau \Delta max} \tag{3}$$

Where $\lambda_i(A)$ is the GRC, Δ_{oi} is deviation among $y_o*(k)$ and $y_i*(k)$.

$y_o*(A)$ = ideal (reference) sequence.

Δ max =highest value of $\Delta_{oi}(A)$,

Δ min = least value of $\Delta_{oi}(A)$ and as the multi response characteristics consist both larger the better and smaller the better, the distinguishing coefficient (τ) is assumed as 0.5.

Grey Relation Grade: The grey relational grades (GRG) (Ґi) are derived by taking average of the GRC, related to every observation as presented in Equation (4).

$$\xi_i = \frac{1}{v}\sum_1^Q i(A) \tag{4}$$

Where, Q =total quantity of responses and v denotes the quantity of measured responses. The GRG (ξ_i) symbolizes the amount of relationship among the reference or ideal sequence and the comparative sequence. If larger GRG occurred than the equivalent set of process parameter is nearer to the most favourable optimal setting. Grey relational coefficients, GRG values are presented in Table 7 and Ranking was done for the GRG values in descending order.

Table 7: Grey Relational Coefficient, GRG and Rank

Exp. No.	TS(MPa)	IS(J)	Hardness(HV)	% Elongation	Bead Width	GRG Values	Ranking
1	0.401834862	0.698113208	0.590909091	0.459459459	0.97826087	0.625715498	10
2	0.33640553	0.521126761	0.534979424	0.346938776	0.816696915	0.511229481	22
3	0.333333333	0.46835443	0.546218487	0.333333333	0.454545455	0.427157008	29
4	0.417142857	0.406593407	0.599078341	0.459459459	0.588235294	0.494101872	25
5	0.407821229	0.415730337	0.590909091	0.459459459	0.426136364	0.460011296	27
6	0.353796446	0.480519481	0.550847458	0.361702128	0.803571429	0.510087388	23
7	0.380869565	1	0.537190083	0.414634146	0.431861804	0.55291112	20
8	0.375643225	0.456790123	0.517928287	0.395348837	0.675675676	0.48427723	26
9	0.356097561	0.333333333	0.555555556	0.361702128	0.497237569	0.420785229	30
10	0.378238342	0.627118644	0.476190476	0.395348837	0.417827298	0.458944719	28
11	0.722772277	0.435294118	0.773809524	0.548387097	1	0.696052603	2
12	0.879518072	0.46835443	0.553191489	0.80952381	0.408348457	0.623787252	11
13	0.763066202	0.627118644	0.562770563	0.62962963	0.849056604	0.686328328	4
14	0.489932886	0.536231884	0.56768559	0.485714286	0.398582817	0.495629492	24
15	1	0.521126761	0.530612245	1	0.355450237	0.681437848	5
16	0.845559846	0.406593407	0.593607306	0.739130435	0.777202073	0.672418613	7
17	0.704180064	0.521126761	0.680628272	0.515151515	0.504484305	0.585114183	16
18	0.613445378	0.480519481	0.513833992	0.485714286	0.880626223	0.594827872	13
19	0.708737864	0.725490196	0.5	0.548387097	0.671641791	0.63085139	9
20	0.699680511	0.536231884	0.465949821	0.515151515	0.47318612	0.53803997	21
21	0.808118081	0.480519481	0.422077922	0.68	0.862068966	0.65055689	8
22	0.699680511	0.456790123	0.828025478	0.548387097	0.38330494	0.58323763	17
23	0.826415094	0.480519481	0.546218487	0.68	0.844277674	0.675486147	6
24	**0.83908046**	**0.536231884**	**1**	**0.739130435**	**0.863723608**	**0.795633277**	**1**
25	0.858823529	0.456790123	0.593607306	0.80952381	0.333333333	0.61041562	12
26	0.814126394	0.649122807	0.534979424	0.68	0.775862069	0.690818139	3
27	0.727574751	0.435294118	0.333333333	0.548387097	0.916496945	0.592217249	16
28	0.727574751	0.435294118	0.333333333	0.548387097	0.916496945	0.592217249	16
29	0.732441472	0.435294118	0.333333333	0.586206897	0.76142132	0.569739428	19
30	0.727574751	0.435294118	0.333333333	0.548387097	0.916496945	0.592217249	15
31	0.737373737	0.435294118	0.333333333	0.548387097	0.916496945	0.594177046	14
32	0.742372881	0.445783133	0.333333333	0.586206897	0.76142132	0.573823513	18

From Table 7, based on the calculated GRG values it is observed that the twenty fourth experimental run had maximum GRG value. It is confirmed that twenty fourth experimental run is treated as optimized parameters.

3.1.2 ANOVA

In order to analyse the significance and the contribution of each parameter to the closeness coefficient value, ANOVA was carried out and their values are shown in Table 8. This analysis was carried out for a level of significance of 5 %, i.e. for 95 % confidence level.

Table 8: ANOVA of Closeness Coefficient Value

Sl. No.	Parameters	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Percentage Contribution (%)
1	Peak Current	4	0.0665986	0.01664965	3.291763104	41.04
2	Pulse Time	4	0.0241383	0.006034575	1.193081616	14.87
3	Pulse Frequency	4	0.0201867	0.005046675	0.997766233	12.44
4	Background Current	4	0.0391287	0.009782175	1.93401079	24.11
5	Welding Speed	4	0.0122776	0.0030694	0.606843848	7.56
6	Error	11	0.0758696	0.005057973		
7	Total	31	0.2381994			

In General, when F>4, it means that the change in the process parameter has a substantial influence on the quality

characteristic. Therefore, Peak Current (Ip), Pulse Time (tp), Pulse Frequency (f), back ground current (Ib) and welding speed (S) have significant influence on the output response. From Table 8, it is understood that peak current has more percentage of individual contributing parameter, then followed by back ground current, pulse time and pulse frequency and welding speed.

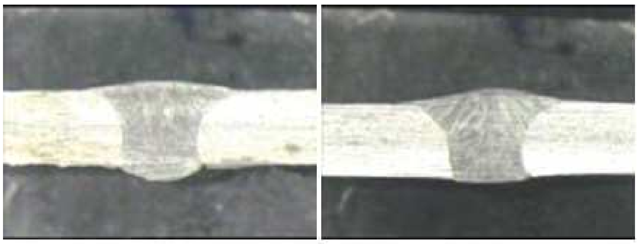
4. CONFIRMATION TEST

The predicted parameters were selected based on the obtained results from the grey relational analysis, which was already conducted in the preliminary welding trials (24th experiment of central composite design). Again for the same 24th set parameters, the welding trial was performed and their processed joints were further investigated through tensile strength, % of elongation, impact, microhardness of the weld and bead profiles. The predicted and experimental results are shown in Table 9.

Table 9: Comparative Results of Conformity Test

Experiment	I_p (Amps)	T_p (Sec)	F_p (Hz)	I_b (Amps)	S (mm/sec)	TS (Mpa)	IS (J)	Hardness (Hv)	% of Elongation	Bead width (mm)
Optimized welding Parameters with predicted values	360	2.7	130	90	40	639	56	481	44	10.83
Experimentally Observed values	360	2.7	130	90	40	642	57	483	44.2	10.79
% of Error	-	-	-	-	-	0.46	1.75	0.41	0.45	0.36

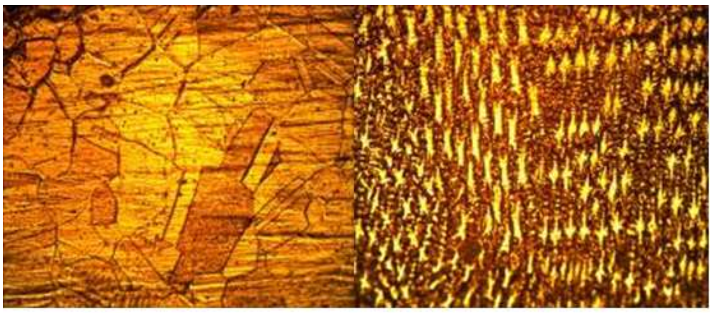
The predicted and experimental bead profiles are shown in Figure 3 (a&b).



(a) Predicted **(b) Experimental**

Figure 3 (a&b): Predicted and Experimental Bead Profiles

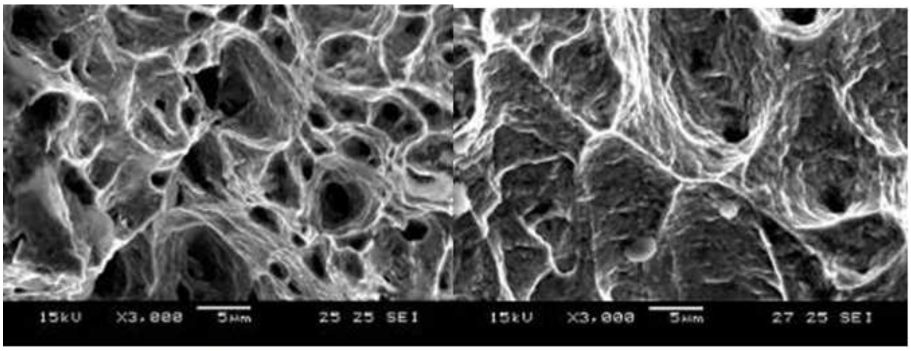
From Figure 3 (a &b) it is observed that, full penetration and normal bead width is achieved. It is evident that full penetration can lead to improve the joint strength. The microstructure of HAZ and weld metal is shown in Figure 4 (a &b).



(a) HAZ **(b) Weld Metal**

Figure 4 (a &b): HAZ and Weld Metal Microstructures of Predicted Parameters

From Figure 4 (a &b) it is found thatthe weld metal contained a fully long columnar dendritic structure with well developed primary arms and clearly distinguishable short secondary arms. It is noted that the primary dendritic arms is a darker phase and secondary interdendritic arms is a lighter phase which can be easily identified through microstructure. Due to the presence of more amount of primary dendritic arms the weld metal hardness values are higher and the obtained grain size are finer. From Table 11, it understood that, tensile properties of the experimentally obtained joints are higher than the predicted strength and base material strength. The impact properties are closer to the base material toughness values. The fracture surface of the tensile and impact specimens analysed through SEM and fractographs are shown in Figure 5.



(a)Tensile SEM fractography (b) Impact SEM Fractography

Figure 5 (a&b): SEM Fractured Surface of Tensile and Impact Tested Samples

Figure 5 (a) shows uniform dimples which would promote the ductile manner under the tensile loading direction. From Figure 5 (b), it is seen that the dimples are in elongated direction and are of finer size. The ductility of the joints depends on the dimple size, if dimple size is finer then ductility of the joint is higher and vice versa. The mode of fracture is ductile. The hardness of the weld joints is higher than the base material hardness. This is due to the finer grain size and high amount of primary dendritic arms present in the weld.

CONCLUSIONS

To optimize the welding process parameter of AISI 904 L super austenitic stainless steel, grey relational analysis was applied in this investigation. The following conclusions can be drawn from the present work:

- Observation concludes that the optimized welding process parameters are peak current-360 amps, pulse time -2.7 secs, frequency-130 Hz, back ground current-90 amps and speed-40 m/min.
- The AVOVA results show that the most effective contributing parameter is peak current (41.04%) followed by back ground current (24.11%), pulse time (14.87%), frequency (12.44%) and welding speed (7.56%) respectively.
- For the optimized parameters, the P-GMA welds were processed and joints exhibited higher tensile, impact strength, % of elongation and hardness of the welds. There was a good agreement between the theoretically predicted and experimentally obtained values.
- The study has proved the feasibility of the grey relational analysis method for solving multi-response optimization problem with P-GMAW process.

- Weld metal grains are finer than the HAZ and base metal and also primary dendritic and secondary interdendritic phases are present.
- Tensile and impact fractured surface appeared in a ductile mode. The weld metal hardness is higher due to finer grain size is present.

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